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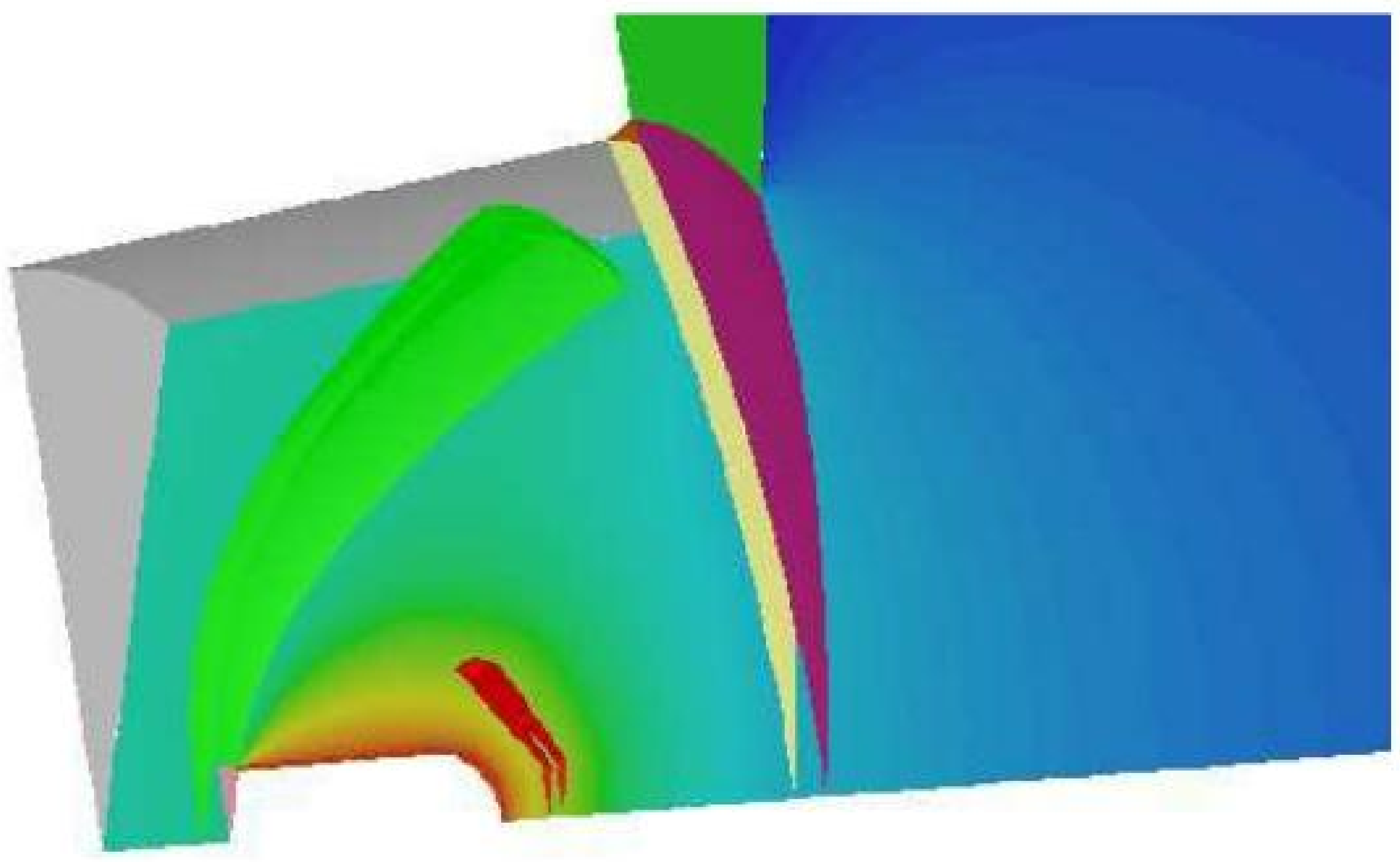
Heat Transfer Modeling



Headlamp modeled with
Discrete Ordinates
Radiation Model

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Outline

- Introduction
- Conjugate Heat Transfer
- Natural Convection
- Radiation
- Periodic Heat Transfer

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Introduction

- Energy transport equation:

$$\frac{\partial}{\partial t}(\rho E)+\nabla\cdot\left(\vec{V}(\rho E+p)\right)=\nabla\cdot\left(k_{eff}\nabla T-\sum_j h_j J_j+(\bar{\bar{\tau}}_{eff}\cdot\vec{V})\right)+S_h$$

  - Energy source due to chemical reaction is included for reacting flows.
  - Energy source due to species diffusion included for multiple species flows.
    - Always included in coupled solver; can be disabled in segregated solver.
  - Energy source due to viscous heating:
    - Describes thermal energy created by viscous shear in the flow.
      - Important when shear stress in fluid is large (e.g., lubrication) and/or in high-velocity, compressible flows.
    - Often negligible
      - not included by default for segregated solver; always included for coupled solver.
  - In solid regions, simple conduction equation solved.
    - Convective term can also be included for moving solids.

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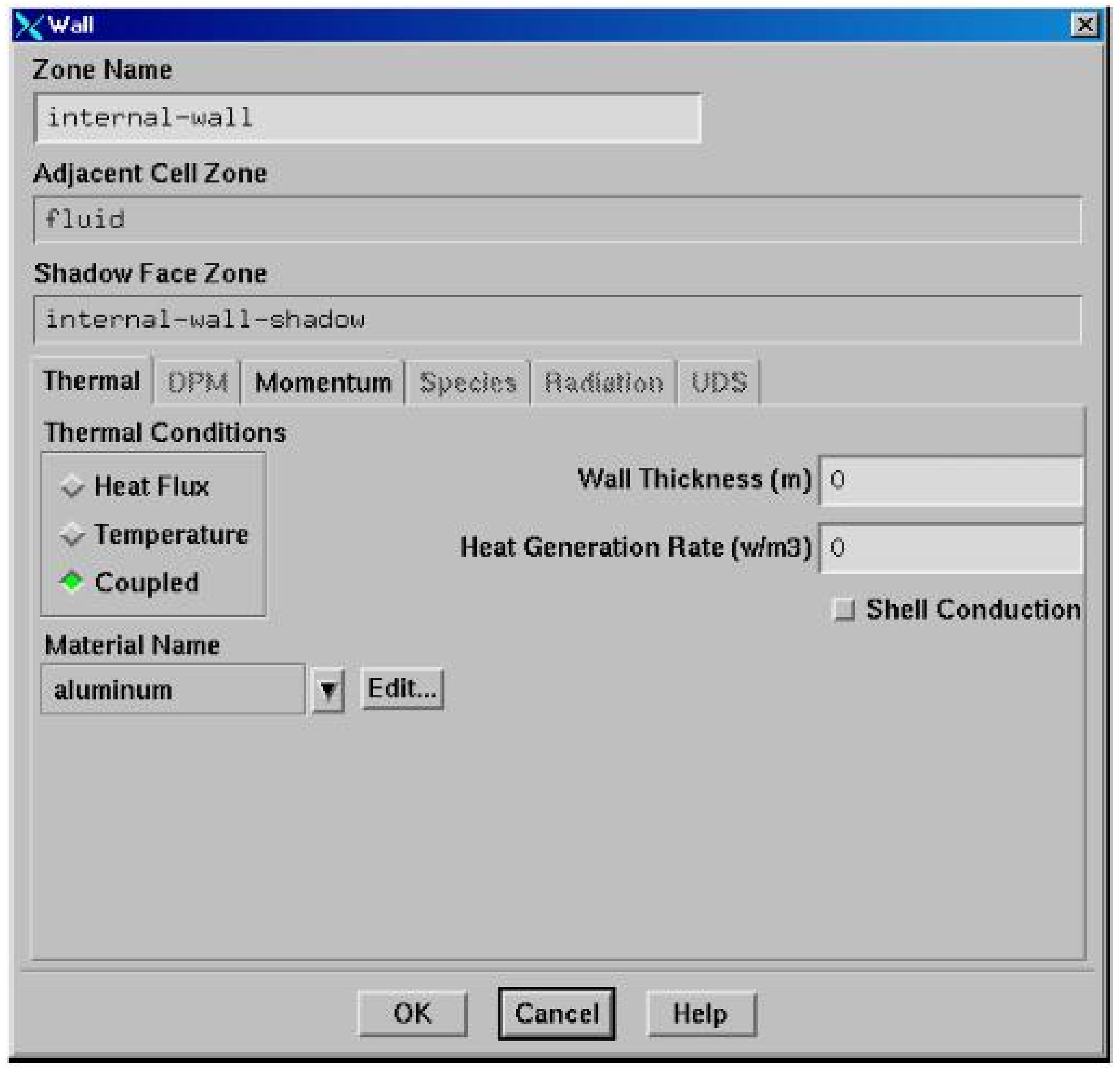
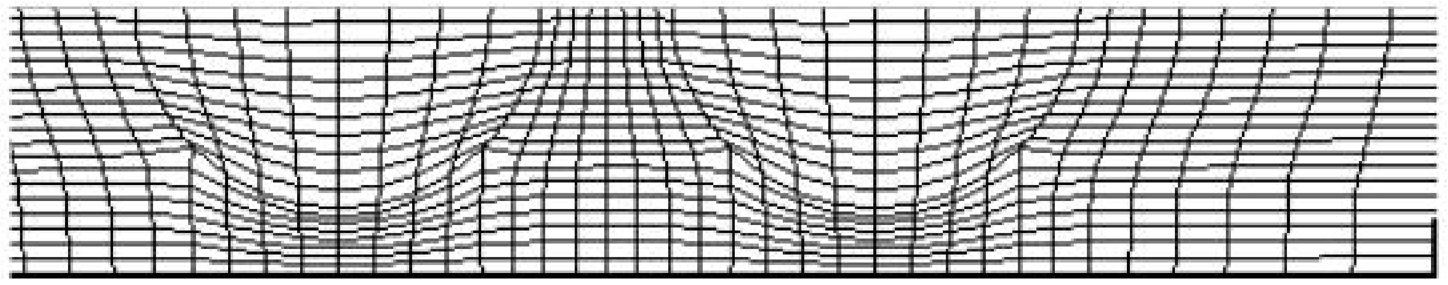
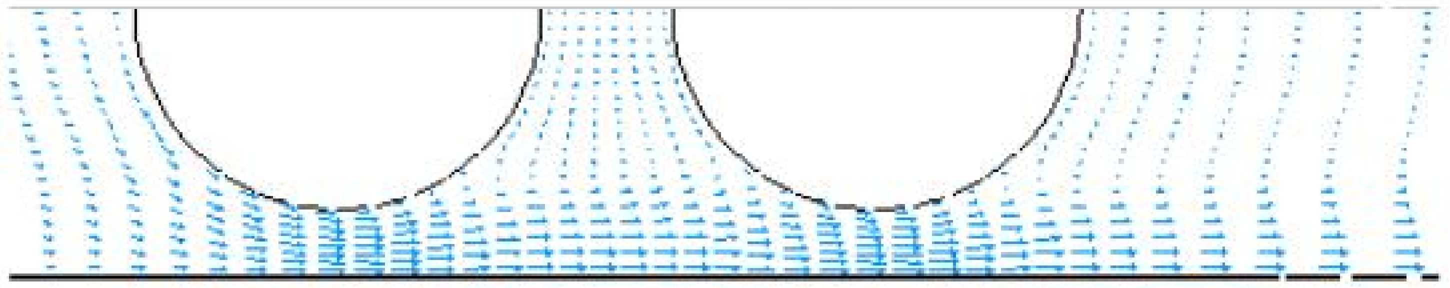
Conjugate Heat Transfer

- Ability to compute conduction of heat through solids, coupled with convective heat transfer in fluid.
- Coupled Boundary Condition:
  - available to wall zone that separates two cell zones.

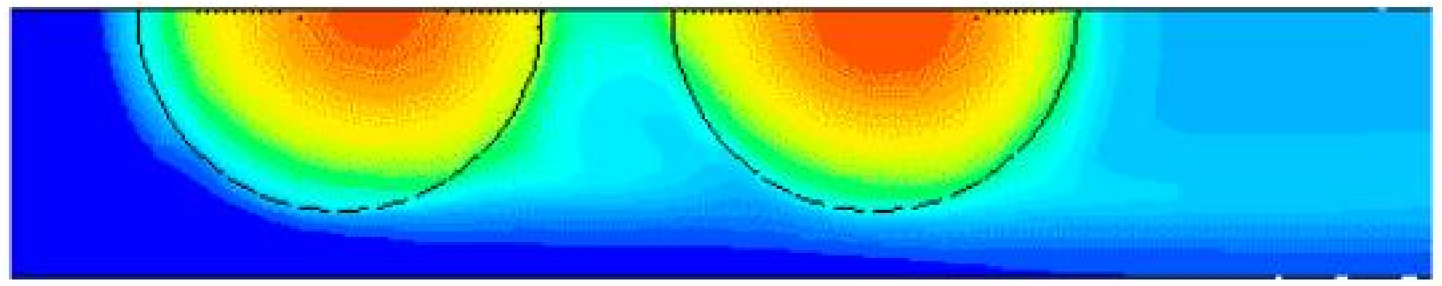




Grid



Velocity vectors



Temperature contours

Example: Cooling flow over fuel rods

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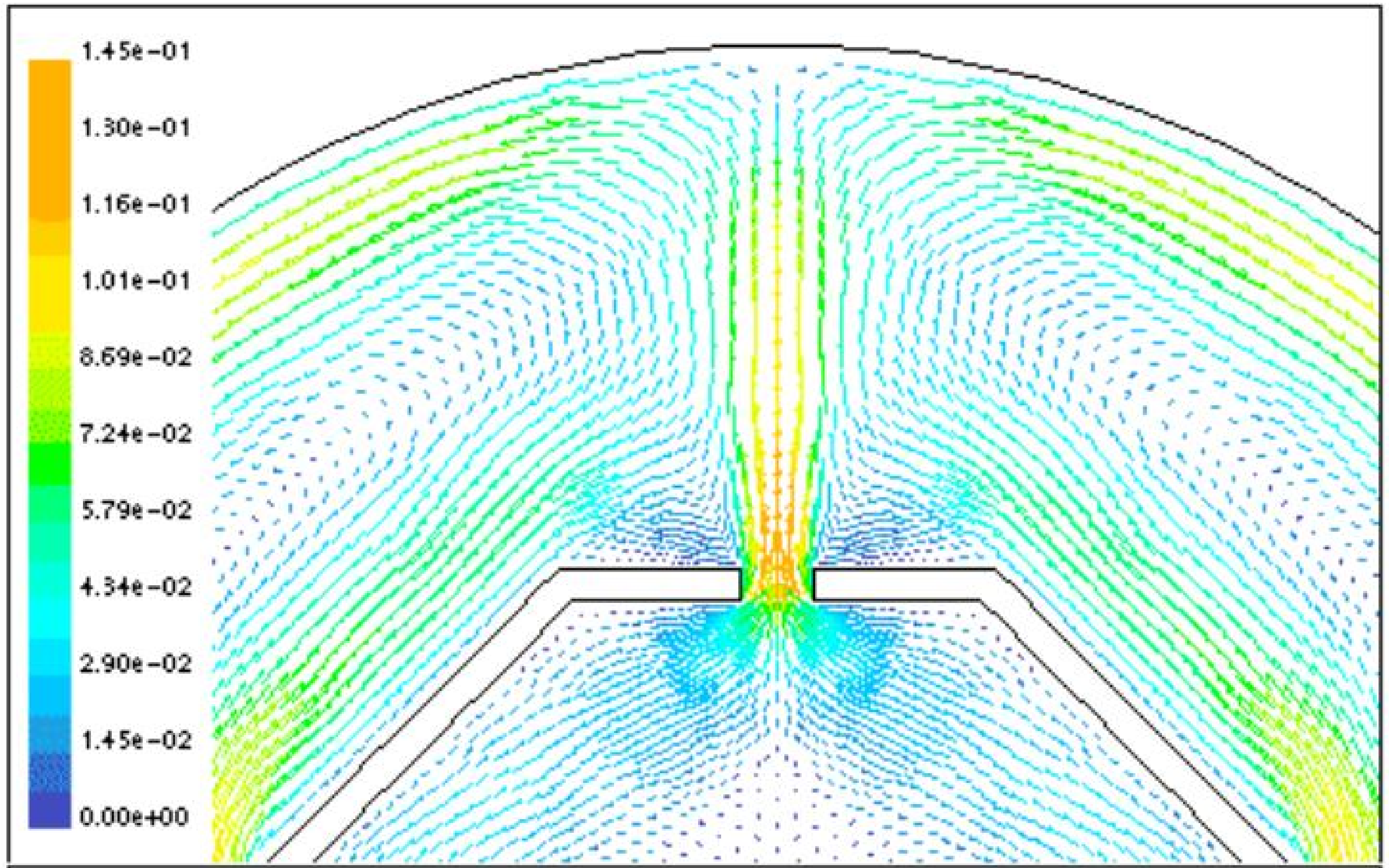
Natural Convection - Introduction

- Natural convection occurs when heat is added to fluid and fluid density varies with temperature.
- Flow is induced by force of gravity acting on density variation.
- When gravity term is included, pressure gradient and body force term in the momentum equation are re-written as:



Natural Convection in a Power Bus Configuration
Velocity Vectors Colored By Velocity Magnitude (m/s)

$$-\frac{\partial p}{\partial x} + \rho g \Rightarrow -\frac{\partial p^{'}}{\partial x} + (\rho - \rho_o) g$$

where $p^{'} = p - \rho_o g x$

- This format avoids potential roundoff error when gravitational body force term is included.

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Natural Convection – the Boussinesq Model

- Boussinesq model assumes the fluid density is uniform
  - *Except* for the body force term in the momentum equation along the direction of gravity, we have:

$$(\rho - \rho_0)g = -\rho_0 \beta (T - T_0)g$$

  - Valid when density variations are small (i.e., small variations in T).
- It provides faster convergence for many natural-convection flows than by using fluid density as function of temperature.
  - Constant density assumptions reduces non-linearity.
  - Suitable when density variations are small.
  - Cannot be used together with species transport or reacting flows.
- Natural convection problems inside closed domains:
  - For steady-state solver, Boussinesq model must be used.
    - The constant density, ρ_o, properly specifies the mass of the domain.
  - For unsteady solver, Boussinesq model or ideal-gas law can be used.
    - Initial conditions define mass in the domain.

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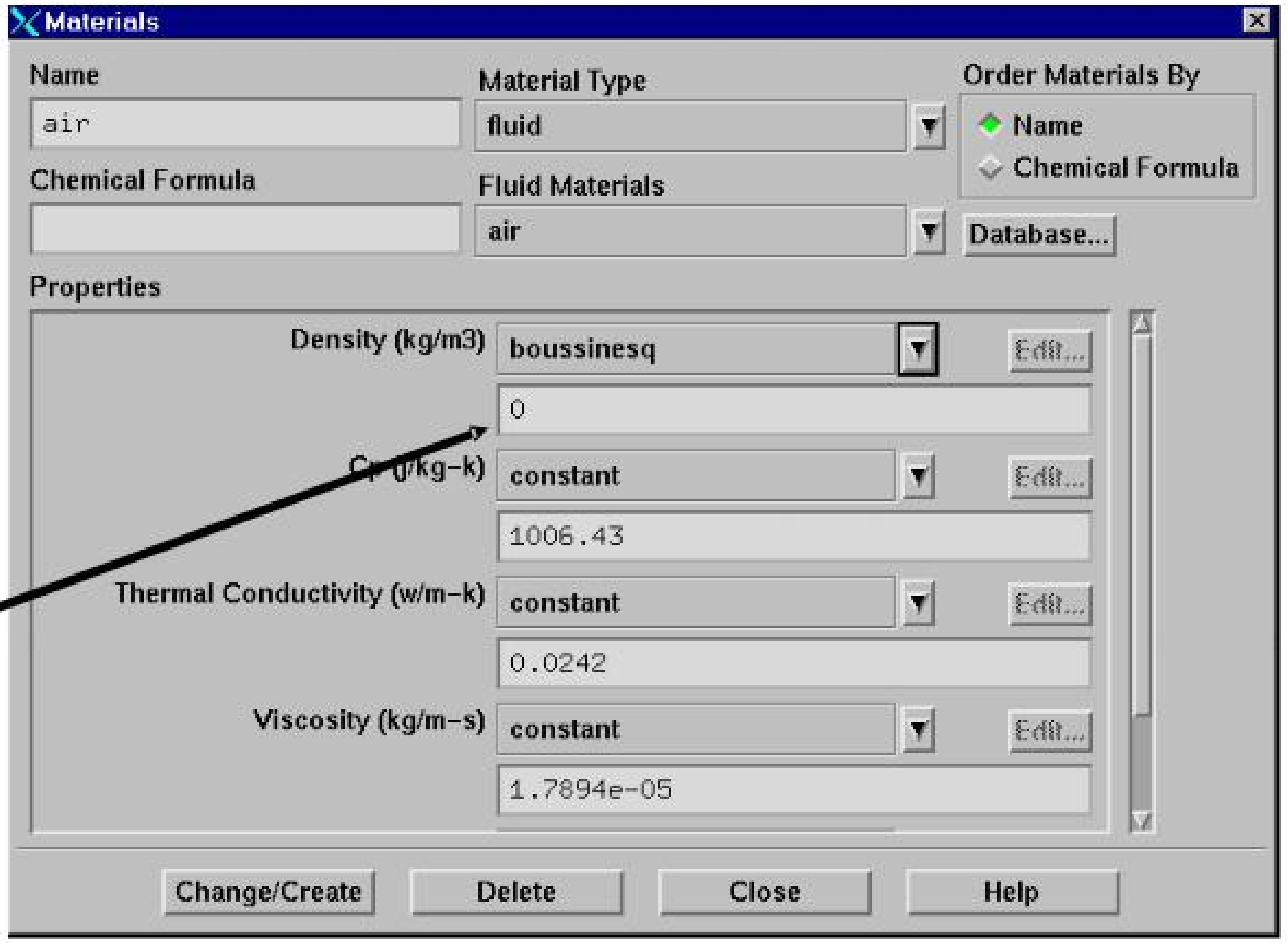
User Inputs for Natural Convection

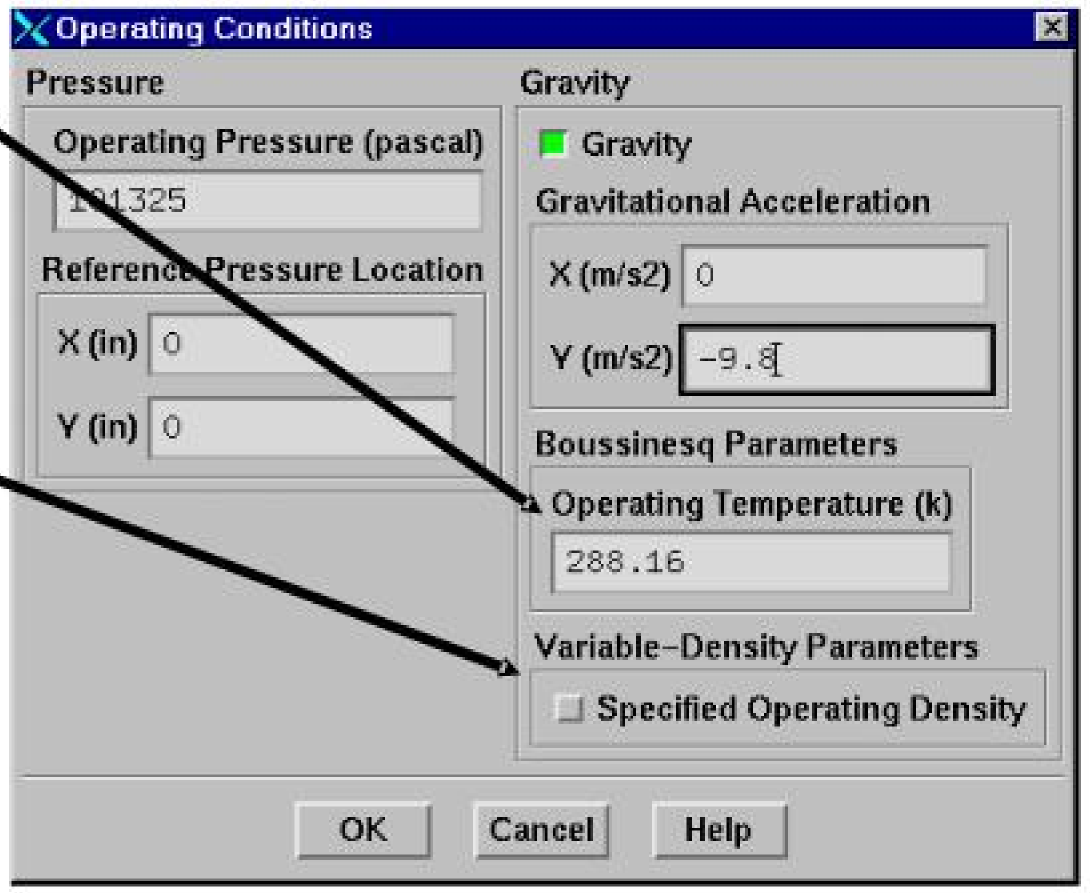
1. Set gravitational acceleration.

   Define → Operating Conditions...

2. Define density model.
   - If using Boussinesq model:
     - Select Boussinesq as the Density method and assign constant value, ρ_o.

       Define → Materials...
     - Set Thermal Expansion Coefficient, β.
     - Set Operating Temperature, T_o.
   - If using temperature dependent model, (e.g., ideal gas or polynomial):
     - Specify Operating Density or,
     - Allow Fluent to calculate ρ_o from a cell average (default, every iteration).





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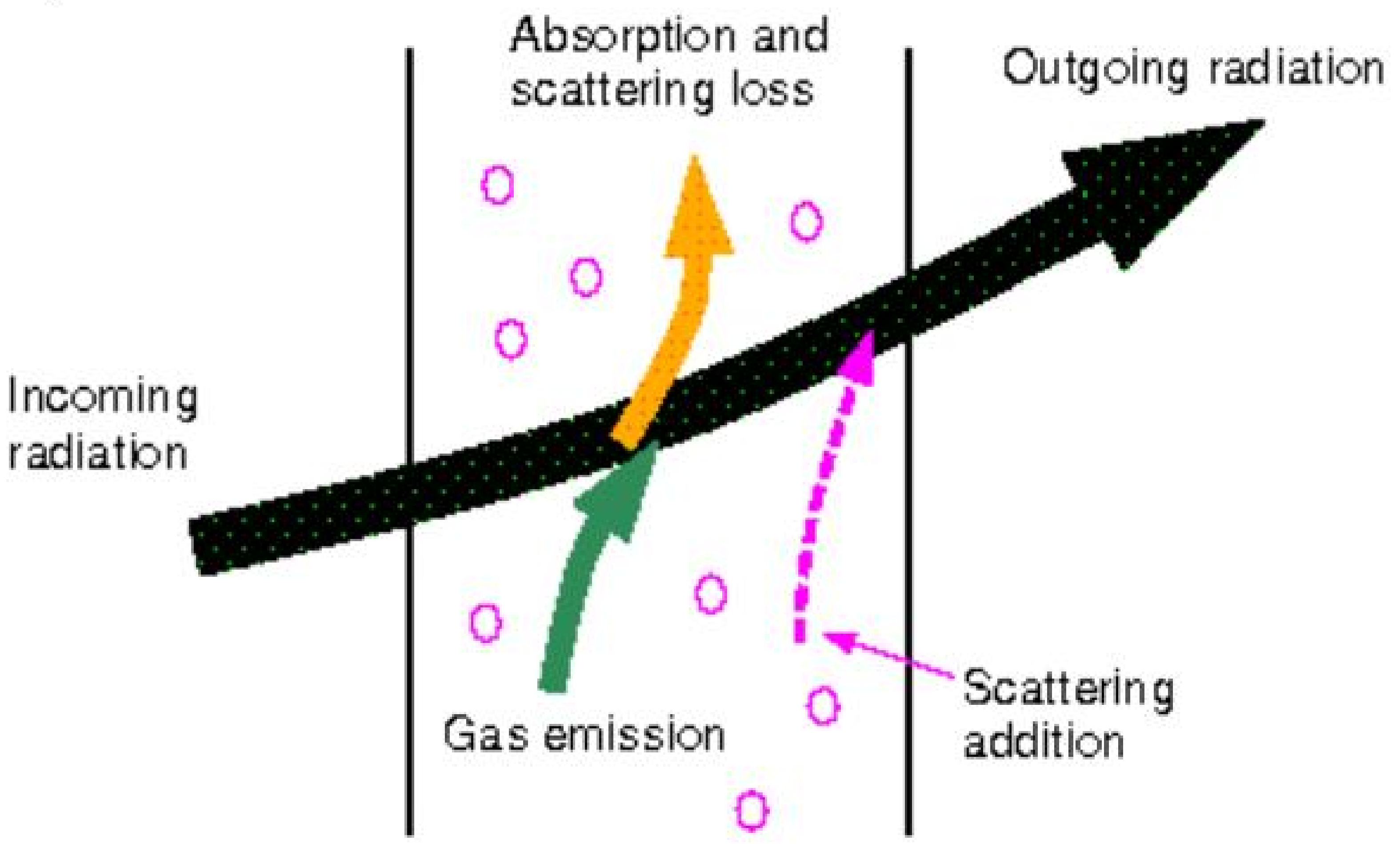
Radiation

- Radiation effects should be accounted for when $Q_{rad} = \sigma(T_{\max}^4 - T_{\min}^4)$ is of equal or greater magnitude than that of convective and conductive heat transfer rates.
- To account for radiation, radiative intensity transport equations (RTEs) are solved.
  - Local absorption by fluid and at boundaries links RTEs with energy equation.
- Radiation intensity, $I(\mathbf{r},s)$, is directionally and spatially dependent.
- Intensity, $I(\mathbf{r},s)$, along any direction can be modified by:
  - Local absorption
  - Out-scattering (scattering away from the direction)
  - Local emission
  - In-scattering (scattering into the direction)
- Five radiation models are provided:
  - Discrete Ordinates Model (DOM)
  - Discrete Transfer Radiation Model (DTRM)
  - P-1 Radiation Model
  - Rosseland Model
  - Surface-to-Surface (S2S)



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Discrete Ordinates Model

- The radiative transfer equation is solved for a discrete number of finite solid angles, s_i:

$$\frac{\partial I_{s\,i}}{\partial x_i} + \underbrace{(a+\sigma_s)I(r,s)}_{\text{absorption}} = \underbrace{an^2\frac{\sigma T^4}{\pi}}_{\text{emission}} + \underbrace{\frac{\sigma_s}{4\pi}\int_0^{4\pi} I(r,s')\Phi(s\cdot s')\,d\Omega'}_{\text{scattering}}$$

- Advantages:
  - Conservative method leads to heat balance for coarse discretization.
    - Accuracy can be increased by using a finer discretization.
  - Most comprehensive radiation model:
    - Accounts for scattering, semi-transparent media, specular surfaces, and wavelength-dependent transmission using banded-gray option.
- Limitations:
  - Solving a problem with a large number of ordinates is CPU-intensive.

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Discrete Transfer Radiation Model (DTRM)

- Main assumption: radiation leaving surface element in a specific range of solid angles can be approximated by a single ray.
- Uses ray-tracing technique to integrate radiant intensity along each ray:

$$\frac{dI}{ds} + aI = \frac{a\sigma T^4}{\pi}$$

- Advantages:
  - Relatively simple model.
  - Can increase accuracy by increasing number of rays.
  - Applies to wide range of optical thicknesses.
- Limitations:
  - Assumes all surfaces are diffuse.
  - Effect of scattering not included.
  - Solving a problem with a large number of rays is CPU-intensive.

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P-1 Model

- Main assumption: Directional dependence in RTE is integrated out, resulting in a diffusion equation for incident radiation.
- Advantages:
  - Radiative transfer equation easy to solve with little CPU demand.
  - Includes effect of scattering.
    - Effects of particles, droplets, and soot can be included.
  - Works reasonably well for combustion applications where optical thickness is large.
- Limitations:
  - Assumes all surfaces are diffuse.
  - May result in loss of accuracy, depending on complexity of geometry, if optical thickness is small.
  - Tends to overpredict radiative fluxes from localized heat sources or sinks.

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Surface-to-Surface Radiation Model

- The S2S radiation model can be used for modeling enclosure radiative transfer without participating media.
  - e.g., spacecraft heat rejection system, solar collector systems, radiative space heaters, and automotive underhood cooling
  - View-factor based model
  - Non-participating media is assumed.
- Limitations:
  - The S2S model assumes that all surfaces are diffuse.
  - The implementation assumes gray radiation.
  - Storage and memory requirements increase *very* rapidly as the number of surface faces increases.
    - Memory requirements can be reduced by using clusters of surface faces.
      - Clustering does not work with sliding meshes or hanging nodes.
  - Not to be used with periodic or symmetry boundary conditions.
  - Cannot be used for models with multiple enclosures geometry.

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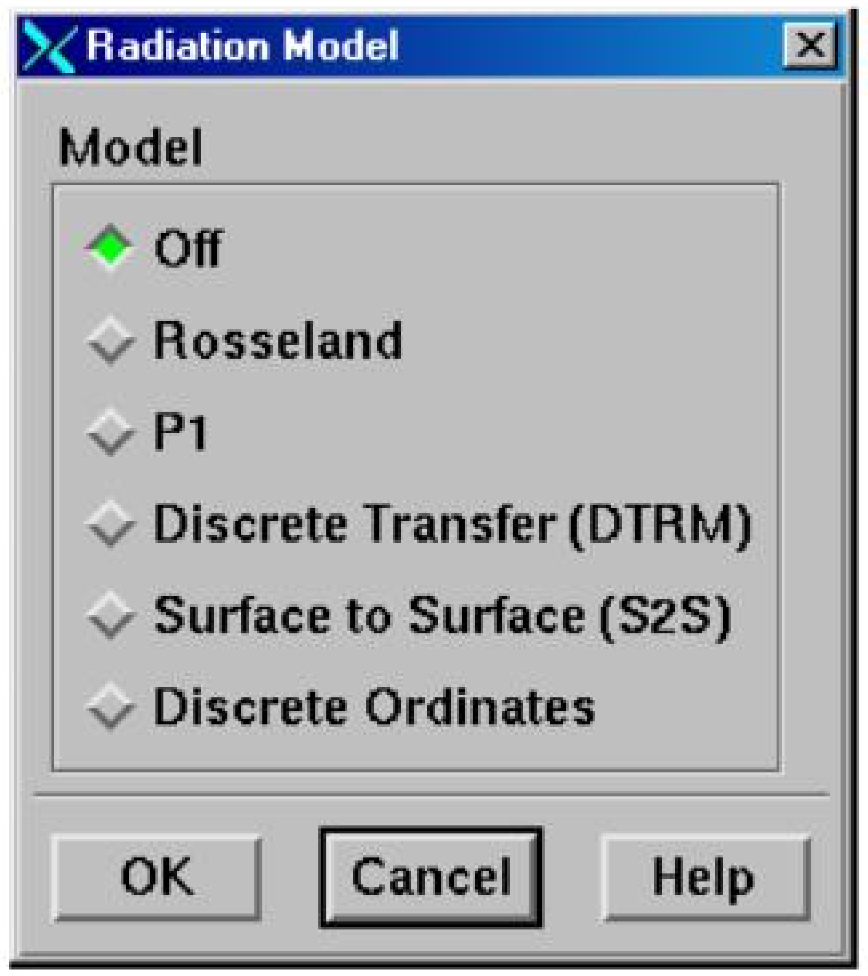
Choosing a Radiation Model

- For certain problems, one radiation model may be more appropriate in general.

  Define → Models → Radiation...

  - Computational effort: P-1 gives reasonable accuracy with less effort.
  - Accuracy: DTRM and DOM more accurate.
  - Optical thickness: DTRM/DOM for optically thin media (optical thickness << 1); P-1 better for optically thick media.
  - Scattering: P-1 and DOM account for scattering.
  - Particulate effects: P-1 and DOM account for radiation exchange between gas and particulates.
  - Localized heat sources: DTRM/DOM with sufficiently large number of rays/ ordinates is more appropriate.

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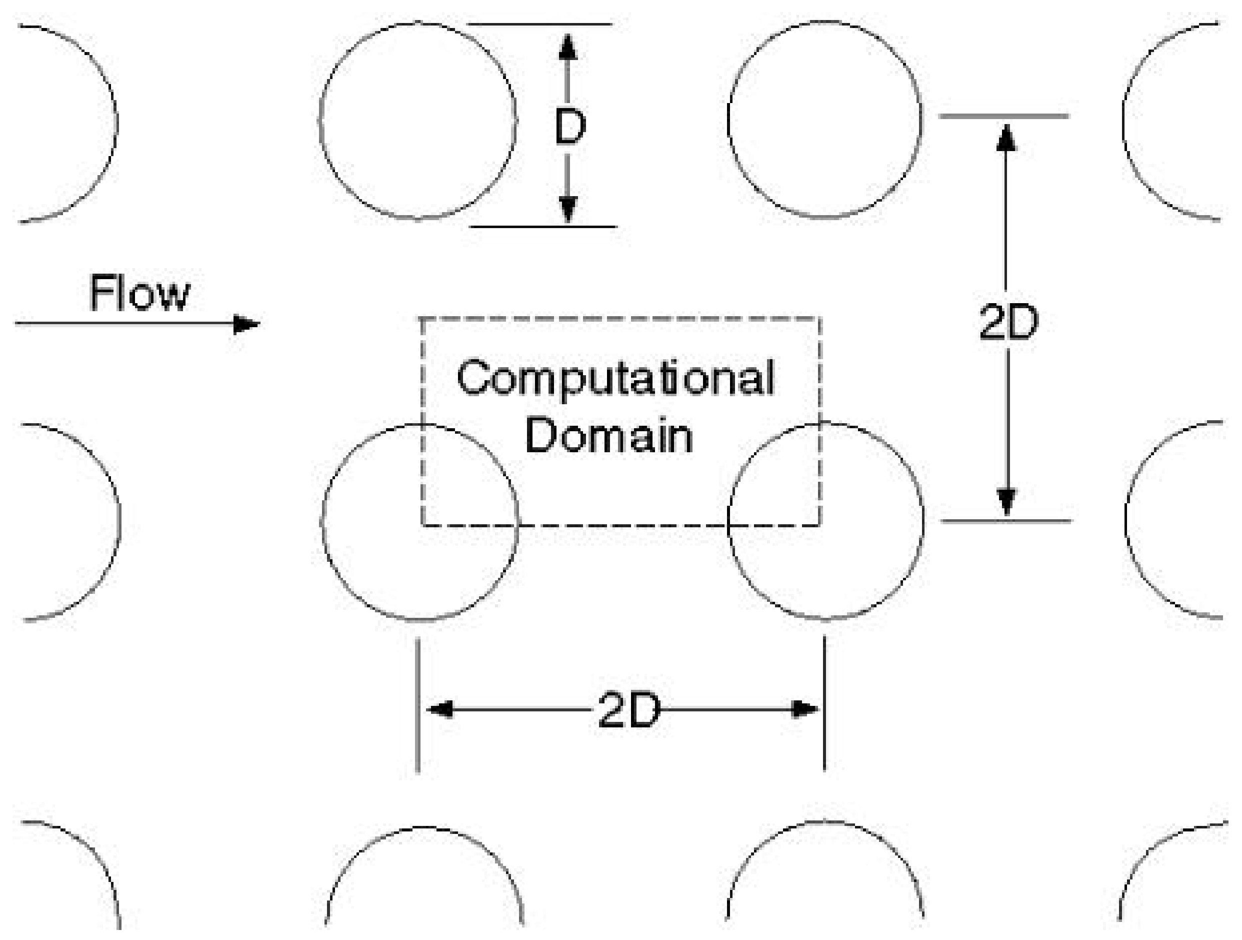
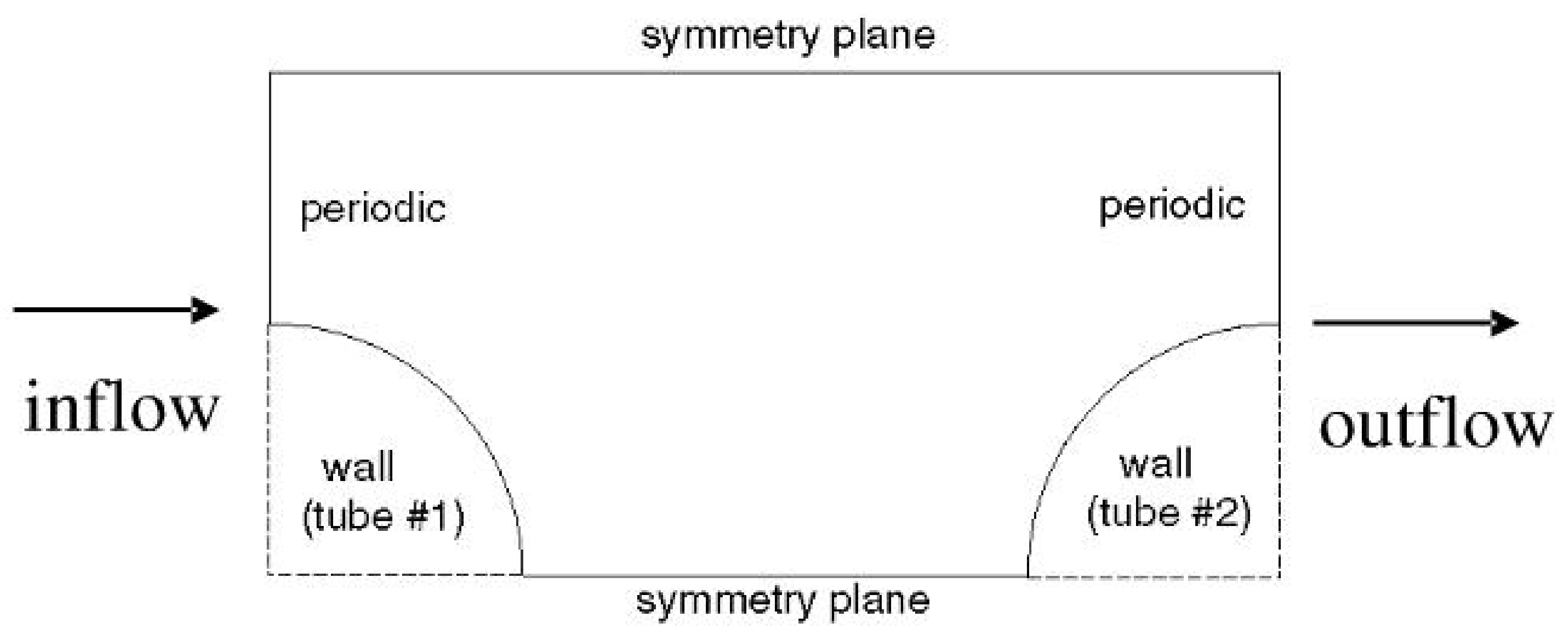
Periodic Heat Transfer (1)

- Also known as streamwise-periodic or fully-developed flow.
- Used when flow and heat transfer patterns are repeated, e.g.,
  - Compact heat exchangers
  - Flow across tube banks
- Geometry and boundary conditions repeat in the streamwise direction.





Outflow at one periodic boundary is inflow at the other

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Periodic Heat Transfer (2)

- Temperature (and pressure) vary in the streamwise direction.
- Scaled temperature (and periodic pressure) is same at periodic boundaries.
- For fixed wall temperature problems, scaled temperature defined as:

$$\theta = \frac{T - T_{wall}}{T_b - T_{wall}}$$

T_b = suitably defined bulk temperature

- Can also model flows with specified wall heat flux.

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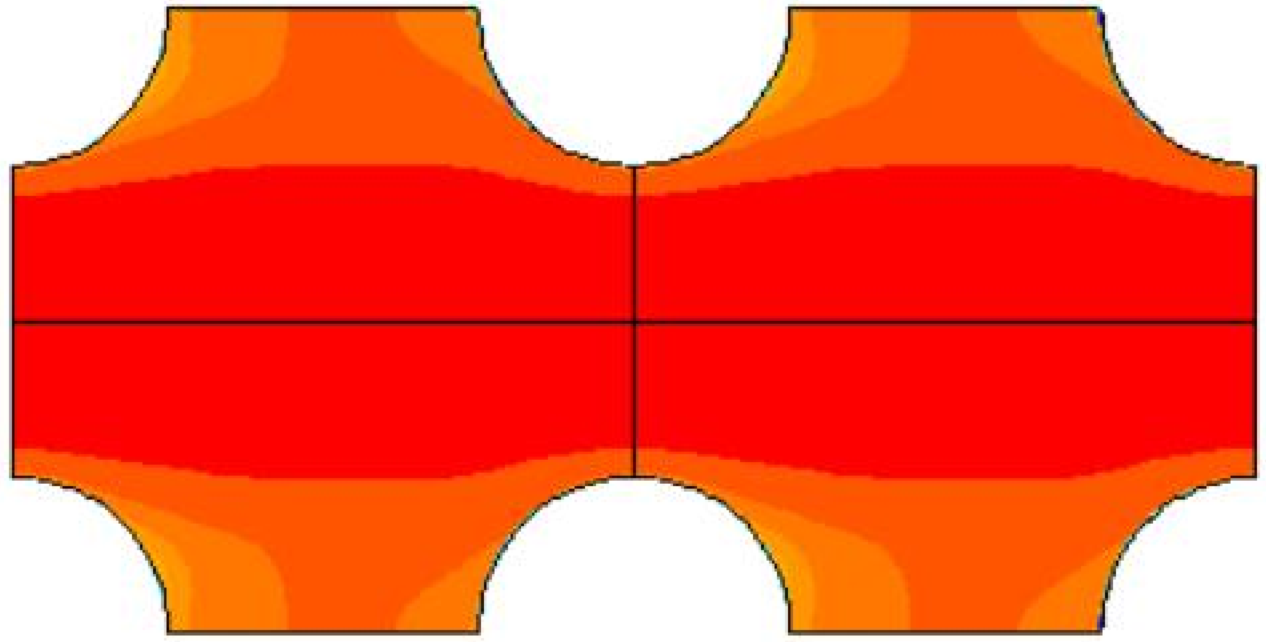
Periodic Heat Transfer (3)

- Periodic heat transfer is subject to the following constraints:
  - Either constant temperature or fixed flux bounds.
  - Conducting regions cannot straddle periodic plane.
  - Thermodynamic and transport properties cannot be functions of temperature.
  - Viscous heating and volumetric heat sources cannot be used with constant wall temperature boundary conditions.



Contours of Scaled Temperature

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Summary

- Heat transfer modeling is available in all Fluent solvers.
- After activating heat transfer, you must provide:
  - Thermal conditions at walls and flow boundaries
  - Fluid properties for energy equation
- Available heat transfer modeling options include:
  - Species diffusion heat source
  - Combustion heat source
  - Conjugate heat transfer
  - Natural convection
  - Radiation
  - Periodic heat transfer

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